Production and decay of charmed baryons: spectra of muons and asymmetry between μ^+ and μ^-

O. I. Piskounova[1,*] and N. V. Nikitin[2,†]

[1]*Lebedev Physics Institute, Russian Academy of Sciences, Moscow*

[2]*SINP Moscow State University, Russia*

The calculation of muon spectra from the decay of Λ_c baryons was carried out on the basis of the description of recent data on charmed-baryon production in hadronic interactions. Data are described in the framework of Quark–Gluon String Model that allowes us to consider primary proton interactions of arbitrary high energy. MC code was built for charmed-baryon semileptonic decay in order to obtain the kinematical characteristics of resulting particles. It is predicted that the charge asymmetry between energy spectra of μ^+ and μ^- in laboratory system is clearly seen as the consequence of asymmetry between the spectra of charmed baryons and antibaryons.This extension of QGS Model can be useful to correct the calculations of muon and neutrino spectra in astrophysics.

Introduction

Charmed-particle decay is an important source of atmospheric muons and neutrinos [1]. We know the characteristics of charmed-hadron production, investigated in the recent years by many fixed-target experiments in accelerators [2]. Model of Quark–Gluon Strings (QGSM) [3] that has been built last two decades can reproduce the energy ditributions of charmed baryons and mesons in hadronic collisions up to very high energies. These spectra have an interesting behavior in the central region of x_{F}: the asymmetry between particle and antiparticle distributions shows a narrow dip for charmed baryons, otherwise the charmed meson asymmetry goes down slowly and reaches a nonzero value in the central x_{F} region, that contradicts the basical QCD theory. Practically it is not possible to reproduce nonzero asymmetry in perturbative QCD approach due to the equal rate of c and $\bar{c}$ production in perturbative gluon fusion process. These phenomena have found an

*E-mail address: piskoun@sci.lebedev.ru

†E-mail address: nik679@monet.npi.msu.su

explanation in recent calculations in the framework of QGSM [4]. It seems interesting to investigate what sort of peculiarities should be produced by this dip in the spectra of muons and neutrino.

I. PRODUCTION OF CHARMED BARYONS IN pp INTERACTIONS AND QGSM

The inclusive-production cross section of hadrons of type H is written as a sum over n-Pomeron cylinder diagrams:

$$f_1 = x\frac{d\sigma^H}{dx}(s,x) = \int E\frac{d^3\sigma^H}{d^3p}d^2p_\perp = \sum_{n=0}^{\infty}\sigma_n(s)\varphi_n^H(s,x). \tag{1}$$

Here, the function $\varphi_n^H(s,x)$ is a particle distribution in the configuration of n-cut cylinders and σ_n is the probability of this process. The cross sections σ_n depend on the parameter of the supercritical Pomeron Δ_{P}, which is equal in our model to 0.12 [3]. In the case of Λ_c production in proton fragmentation the diquark fragmentation plays an important role, this diquark part of distribution should be written separately. So the distribution for pp collision will include two diquark parts for positive x as well as for negative:

$$\begin{aligned}\varphi_n^{\Lambda_c}(s,x) = a_f^{\Lambda_c}F_{1qq}^{(n)}(x_+) + a_f^{\Lambda_c}F_{1qq}^{(n)}(x_-) + a_0^{\bar{\Lambda}_c}[F_q^{(n)}(x_+)F_{0qq}^{(n)}(x_-) + \\ +F_{0qq}^{(n)}(x_+)F_q^{(n)}(x_-) + 2(n-1)F_{q_{sea}}^{(n)}(x_+)F_{\bar{q}_{sea}}^{(n)}(x_-)],\end{aligned} \tag{2}$$

where $F_{1qq}^{(n)}(x_+)$ is the distribution at the leading fragmentation of diquarks, while $F_{0qq}^{(n)}(x_+)$ is the ordinary part of fragmentation written with the central density parameter $a_0^{\bar{\Lambda}_c}$. Obviously, the distribution for $\bar{\Lambda}_c$ does not include the leading fragmentation term.

The fragmentation functions of diquark and quark chains into charmed baryons or antibaryons are based on the rules written in [5]. The structure functions of quarks in interacting proton have already been described in the previous papers [6, 7, 8]. The asymmetry between the spectra of Λ_c and $\bar{\Lambda}_c$ measured in pA collisions at p_L= 600 GeV/c [9] is shown in Fig.1a.

The asymmetry is defined as

$$A(x) = \frac{dN^{\Lambda_c}/dx - dN^{\bar{\Lambda}_c}/dx}{dN^{\Lambda_c}/dx + dN^{\bar{\Lambda}_c}/dx}. \tag{3}$$

Here, dN^{Λ_c}/dx and $dN^{\bar{\Lambda}_c}/dx$ are the event distributions measured in the experiment [9]. The asymmetry plot has the sharp dip in the central region that is peculiar for baryon production in proton–proton collisions.

The invariant distributions xdN/dx of charmed baryons and antibaryons obtained in proton interactions in E781 experiment are shown in Fig.1b with the QGSM curves calculated for proton fragmentation on both sides. It should be mentioned here that usually cosmic protons are interacting with the air nuclei in cosmic-ray physics and spectra are different. But the dependence on atomic number of target nuclei is important at $y < 0$ and, besides, it should be cancelled in formula (3). Thus, our conclusions about asymmetries are valid for proton–nucleus collisions as well.

II. CHARMED BARYON/ANTIBARYON SPECTRA IN LABORATORY SYSTEM

The results of accelerator experiment are presented usually in center of mass system (c.m.) that is not accepted in cosmic-ray physics where the Earth is the only possible laboratory system (lab.) for the measurements. The transformation of spectra at the transition from c.m. to lab. can be done taking into account the invariance of the value $d\sigma/dy = xd\sigma/dx_{c.m.} = d\sigma/dy(y_{lab} - y_0)_{lab}$. In this case we will have the E^{-1} power slope of the spectra in the laboratory system:

$$d\sigma/dE = 1/E(xd\sigma/dx) = 1/E(d\sigma/dy). \tag{4}$$

This slope should be seen in the energy region corresponding to the central plateau of distribution in c.m., where $d\sigma/dy =$ const. The transformed baryon and antibaryon spectra are shown in Fig. 2 at the energy of proton interaction $E_p = 10^4$ GeV.

This method was already used in the calculation of photon spectra from monochromatic cosmic proton sorce [10] and in the estimation of antiproton/proton ratio [11] in cosmic rays. In Fig. 2 we can see also how the asymmetry between spectra behaves in laboratory system. The dip in asymmetry is extending up to the energy of order of $0.1E_p$. Will it be seen in the muon spectra?

III. SPECTRA OF MUONS

In the previous section we have described the calculations of charmed baryons in laboratory system. Here we are giving the brief description of the procedure of the calculation of muon spectra that are generated in semileptonic decays of Λ_c.

It is well known that the rather good approximation to the lepton spectra can be obtained for semileptonic decays of charmed baryons, if one takes the probability of these decays the same as for exclusive parton decay $c \to s\mu^+\nu_\mu$, where c quark posseses the energy and the spectrum of Λ_c.

The decay $c \to s\mu^+\nu_\mu$ has been studied , for example, in [12]. Its differential width is equal to:

$$\frac{d^2\Gamma}{d\hat{s}\,d\hat{t}} = \frac{G_F^2}{16\pi^3}\, m_c^5\, |V_{cs}|^2 \left(1 + \hat{m}_\mu^2 - \hat{t}\right)\left(\hat{t} - \hat{m}_s^2\right), \tag{5}$$

where $\hat{s}, \hat{t}$ are the standart Mandelstam variables, m_c, m_μ are masses of quark and muon. Mandelstam variables $\hat{s}, \hat{t}$ have to satisfy the followig kinematical restrictions:

$$\hat{m}_\mu^2 \le \hat{s} \le \left(1 - \sqrt{\hat{m}_s^2}\right), \qquad \hat{m}_s^2 \le \hat{t} \le \left(1 - \sqrt{\hat{m}_\mu^2}\right). \tag{6}$$

Let us write formula (5) as the expression normalized to the interval 0 to 1 that will be usefull at the construction of Monte-Carlo (MC) generator:

$$w(\hat{s}, \hat{t}) = \frac{4}{\left(1 + \hat{m}_\mu^2 - \hat{m}_s^2\right)^2}\left(1 + \hat{m}_\mu^2 - \hat{t}\right)\left(\hat{t} - \hat{m}_s^2\right). \tag{7}$$

The MC procedure of generating of muon spectra consists of a few steps. First of all we are considering the decay $c \to s\mu^+\nu_\mu$ in the rest system of charmed baryon that is also the rest system of c quark and getting the random pair $\hat{s}, \hat{t}$ from the interval that was written in Eq.(6). This pair is being checked with the help of kinematical function whether it belongs to the physical space of the process (right pair). If the pair is chosen as right it possesses the weight of Eq.(7). The momenta and energies of the decay products are calculated due to s, t.

The revolting on three axes are applied to resulting vectors of momenta that are turned with random Eiler angles to reach the arbitrary positions toward the axes. It helps us to return to the system where Λ_c is moving along the x axis. We are neglecting here the transverse motion because of the small ratio between transverse momentum and longitudinal one.

As the result of described MC procedure, the table of four-momenta of all products of decay is built, where the data for further analysis can be found.

IV. RESULTING PLOTS AND COMPARISONS

In this work we have the possibility to analyze the Λ_c spectra that can be calculated analytically with QGSM for arbitrary energy and at the same time to compare these spectra with the muon spectra that are generating after the decay of charmed baryons. We are interested here in only muon characteristics, but the possibility exists to analyze the neutrino spectra too.

Let us compare the spectra of $\Lambda_c/\bar{\Lambda}_c$ with the spectra of decay products at the energy of initial proton–proton interaction $E_p = 10^8$ GeV. As it can be seen from Fig. 3, the asymmetry predicted

between the spectra of baryons and antibaryons is clearly reproduced in the spectra of μ^+ and μ^-. The spectra of Λ_c are of the same form as it was calculated analytically (see Fig. 2).

The asymmetry between spectra of μ^+ and μ^- that is shown in Fig.4 is almost equal to zero in the wide region corresponding to the central plateau in Λ_c-production distribution. It would be interesting to study how this asymmetry is sensitive to the difference in baryon/antibaryon production at high energies that might remain to be valuable due to the effect of string-junction transfer, wich was not accounted for in our calculations.

V. SUMMARY

In this paper we have studied the spectra of muons after the semileptonic decay of charmed baryons produced in the hadronic interactions at very high energy. It is assumed that the conclusions on this research are interesting for cosmic ray physics as well as for high-energy accelerator physics. The asymmetry in production of baryons over antibaryons is caused by the positive baryonic charge of colliding protons. This asymmetry is to disappear in central region with the rising of interaction energy. The spectra of charmed baryons and antibaryons have been described in Quark–Gluon String Model with the account of quark interaction mechanisms providing the baryon/antibaryon asymmetry. Only the mechanism of string-junction transfer was not accounted yet in our scheme. Even so, the obvious asymmetry is reproduced on the edges of the spectra of $\Lambda_c/\bar{\Lambda}_c$ in laboratory system as it was analytically predicted. The knee in the spectra at 0.1 E_p is caused by the form of analytical spectra in fragmentation region. This very form of spectra in laboratory system can be a good manifestation of the interaction of monochromatic primary protons. The Monte-Carlo generator, which was built for the calculation of spectra of products of charmed baryon decays, provides the four-momenta of all particles after semileptonic decay. We have analyzed here only muon spectra. These spectra reproduce the production asymmetry between positive and negative particles, as it is seen in spectra of the $\Lambda_c/\bar{\Lambda}_c$. We can conclude that muons can be a good instrument to study the baryon production asymmetry in high-energy proton–proton interactions. The estimation of background from D-meson decays should be done in the same QGSM approach.

Acknowledgments

Authors are thankful to Prof. A.B. Kaidalov and Dr. L.V. Volkova for the numerous discussions.One of the authors is supported with the grant of RFBR No.04-02-16757a, the grant RFBR-DFG 03-02-04026a and the grant NATO CLG.980335.

---

[1] F. Halsen *et al.*, Phys. Rev. D **55**, 4475 (1997); EAS-TOP Collab., MACRO Collab., Astropart. Phys. **20**, 641 (2004); K. Abe *et al.*, Phys. Lett. B **564**, 8 (2003); T. Sanuki *et al.*, Phys. Lett. B **541**, 234 (2002); G. Fiorentini,V. A. Naumov, F. L. Villante, Phys. Lett. B **510**, 173 (2001).

[2] R. Vogt, hep-ph/0412303; in*the Proceedings of the Strangenes in Quark Matter, Cape Town, South Africa, 2004.*

[3] A. B. Kaidalov and K. A. Ter-Martirosyan, Sov. J. Nucl. Phys. **39**, 1545 (1984); **40**, 211 (1984); A. B. Kaidalov, Phys. Lett. B **116**, 459 (1982).

[4] A. B. Kaidalov and O. I. Piskounova, Sov. J. Nucl. Phys. **43**, 1545 (1986); O. I. Piskounova, Phys. At. Nucl. **56**, 1094 (1993).

[5] A. B. Kaidalov, Sov. J. Nucl. Phys. **45**, 1450 (1987).

[6] O. I. Piskounova, Nucl. Phys. (Proc.Suppl.) B **93**, 144 (2001).

[7] O. I. Piskounova, Phys. At. Nucl. **64**, 101 (2001).

[8] O. I. Piskounova, *in the Proceedings of the DIS', St.Petersbourg, Russia, April, 2003.*

[9] SELEX Collab.(F. G. Garcia *et al.*), Phys. Lett. B **528**, 49 (2002).

[10] O. I. Piskounova, Sov. J. Nucl. Phys. **51**, 480 (1990).

[11] O. I. Piskounova, Sov. J. Nucl. Phys. **47**, 846 (1988).

[12] V. Novikov *et al.*, Phys. Rev. Lett. **38**, 626 (1977); B. Block, L. Koyrakh, M. Shifman, and A. Vainshtein, Phys. Rev. D **49**, 3356 (1994).

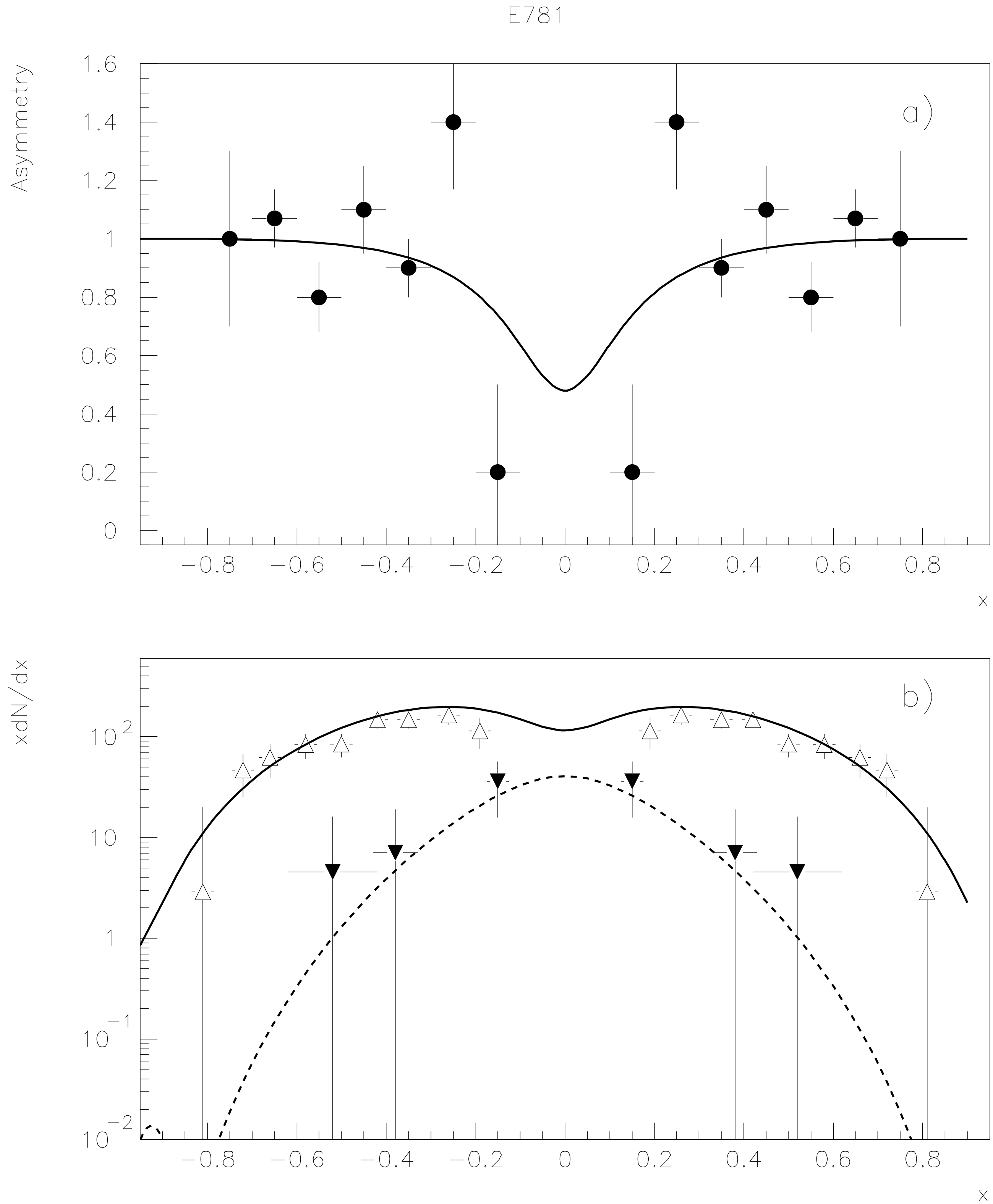


FIG. 1: The asymmetry between Λ_c and $\bar{\Lambda}_c$ spectra obtained for pA collisions in the E781 experiment (black circles) [9], the QGSM calculation (solid line) (a); the distributions of Λ_c (empty triangles) and $\bar{\Lambda}_c$ (black triangles) in E781 for these reactions and QGSM curves: Λ_c (solid line) and $\bar{\Lambda}_c$ (dashed line) (b).

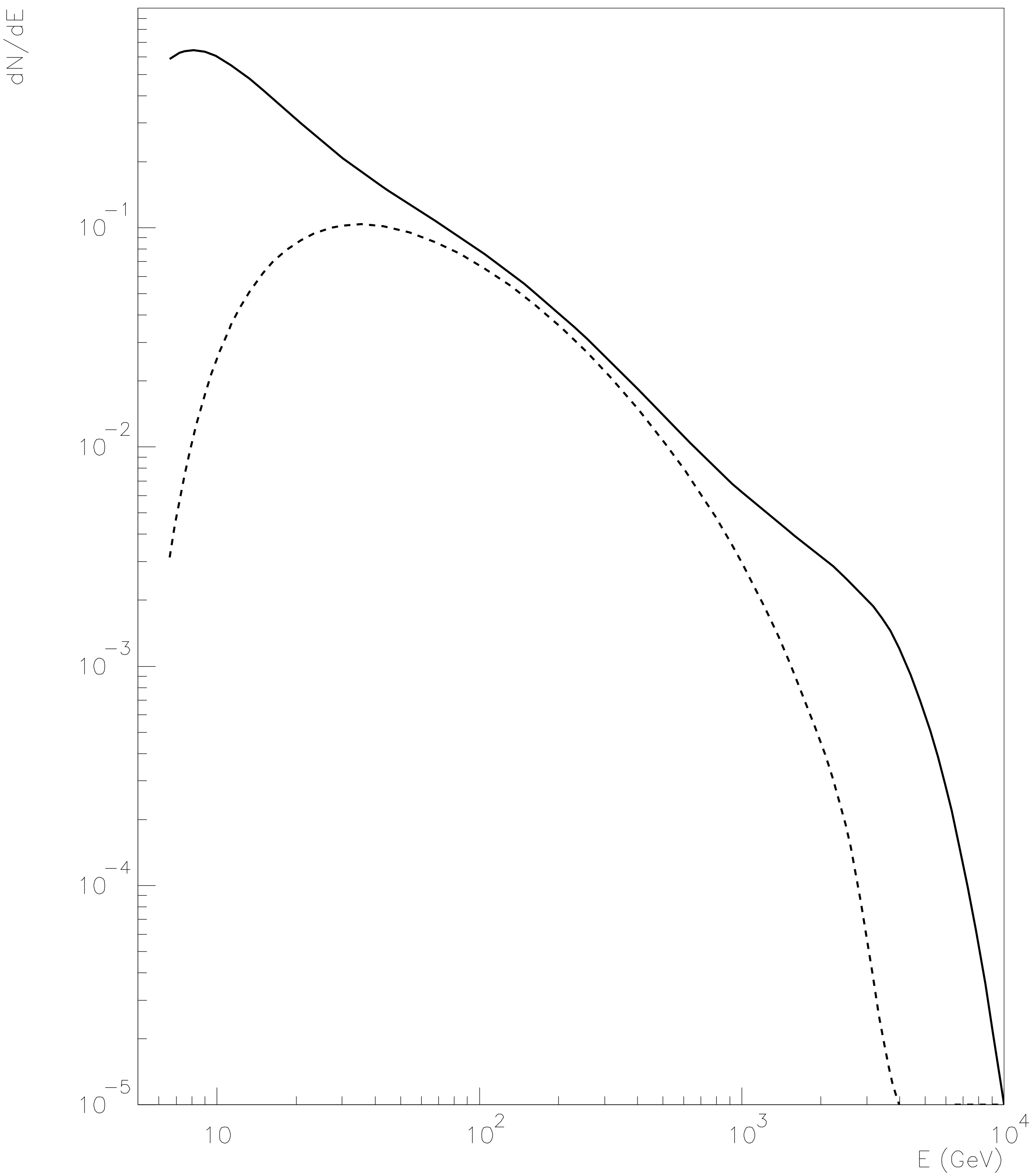
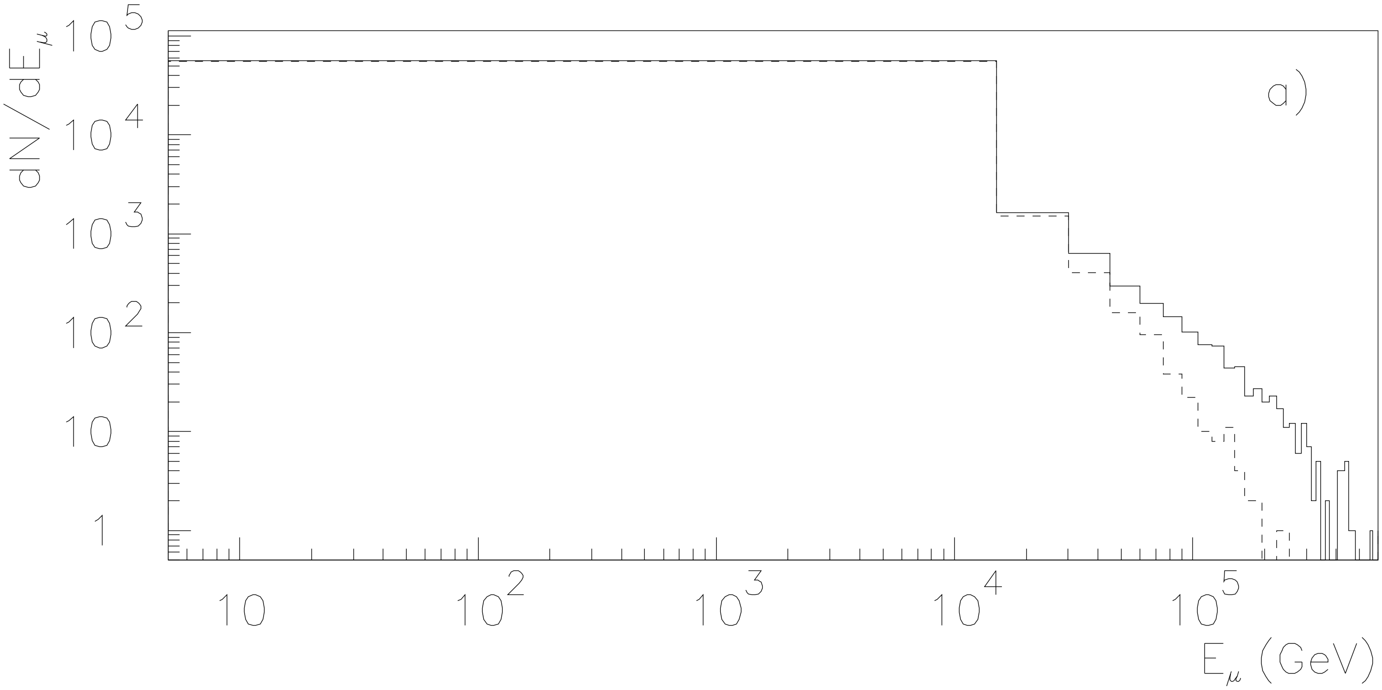


FIG. 2: The distributions of Λ_c (solid line) and $\bar{\Lambda}_c$ (dashed line) laboratory system, calculated in QGSM for the energy $E_p = 10^4$ GeV.



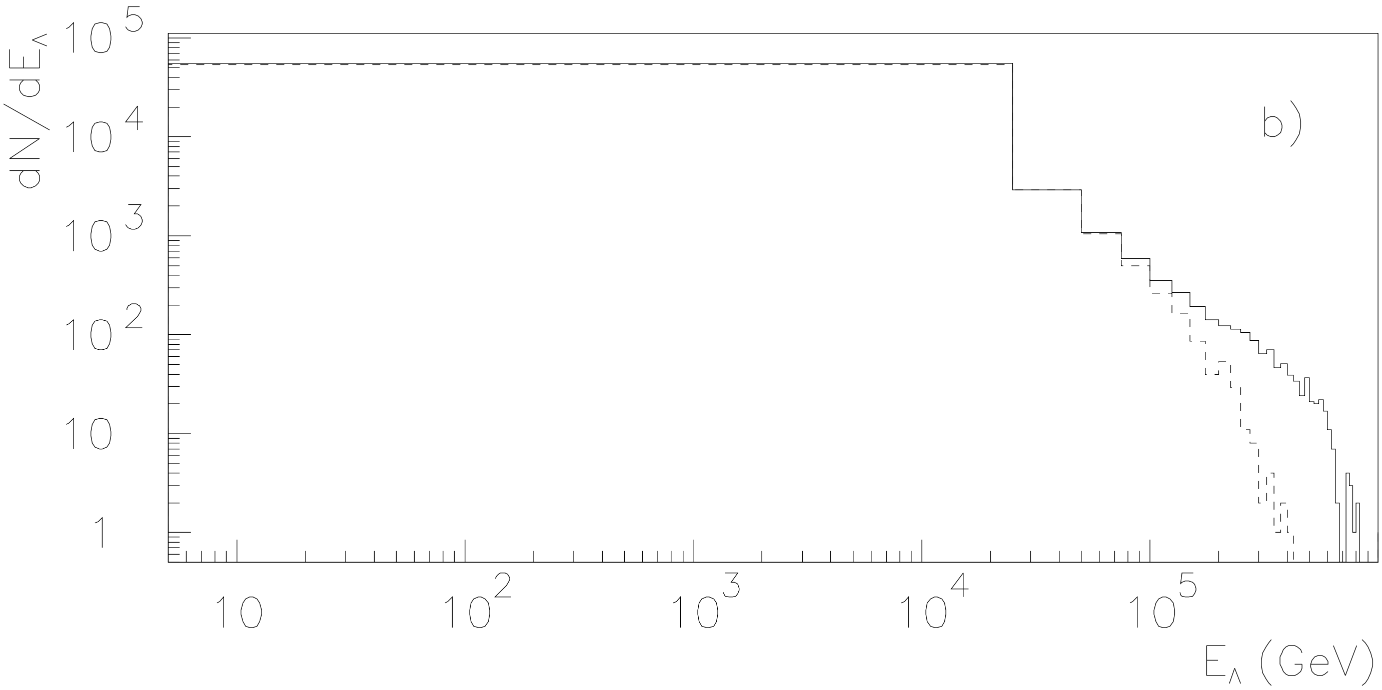
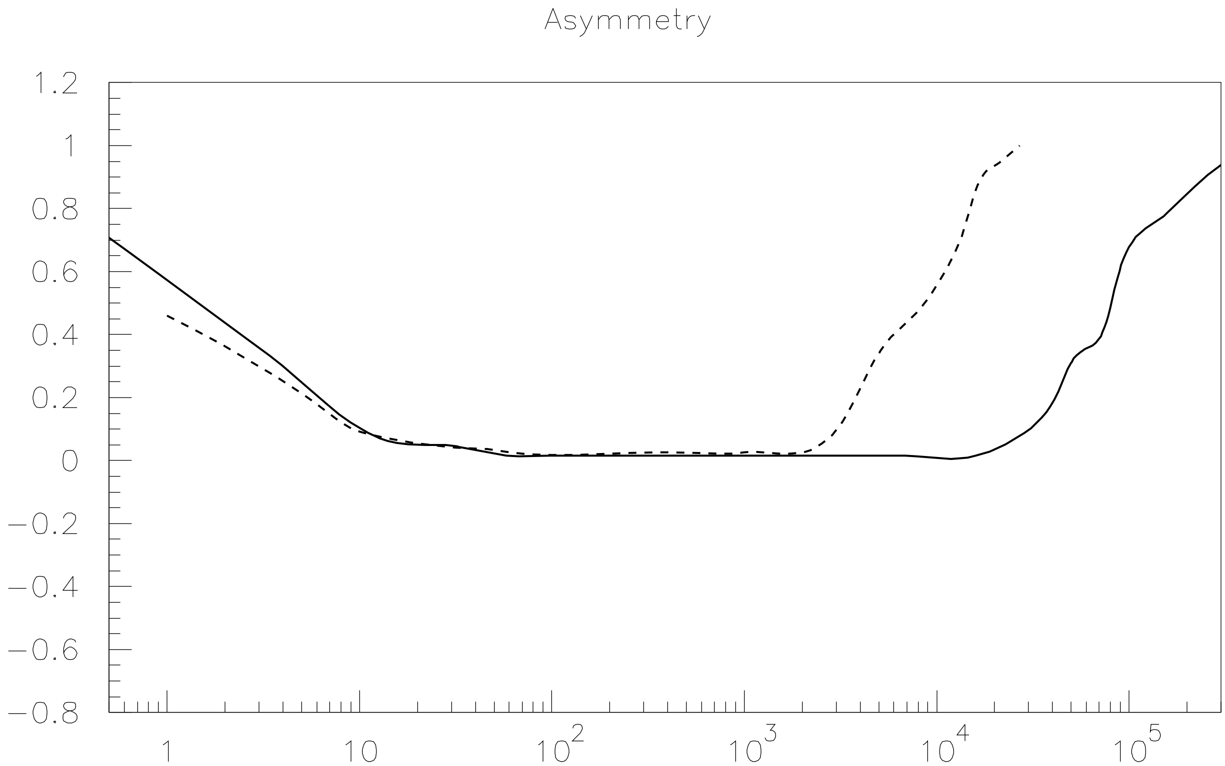


FIG. 3: The spectra of μ^+ (solid line) and μ^- (dashed line) calculated at $E_p = 10^5$ GeV (a); the distributions of Λ_c (solid line) and $\bar{\Lambda}_c$ (dashed line) in QGSM for the energy $E_p = 10^5$ GeV (b).



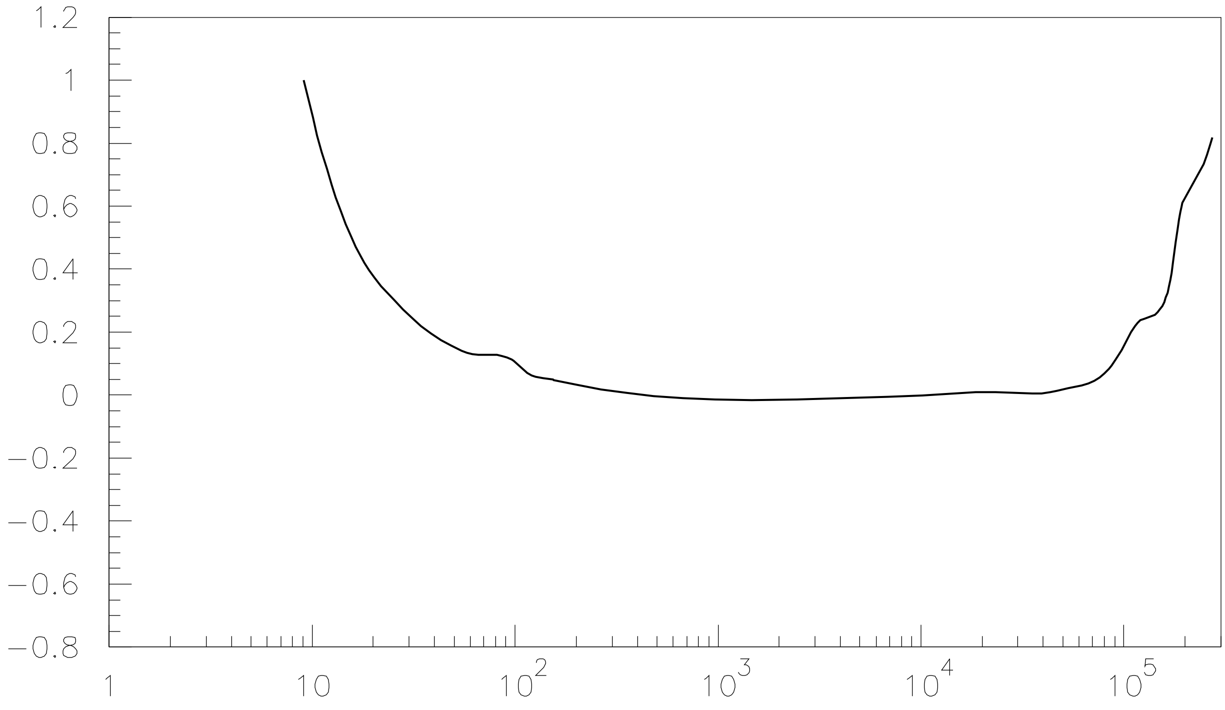


FIG. 4: The asymmetry between spectra of μ^+ and μ^- calculated at $E_p = 10^6$ and 10^5 GeV (dotted line) (a); the asymmetry between Λ_c and $\bar{\Lambda}_c$ spectra obtained for pp collisions in the QGSM calculation at $E_p = 10^6$ GeV (b).